The ATLAS **D**iamond **B**eam **M**onitor

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on behalf of the DBM group

August 16, 2013

<u>Outline of Talk</u>
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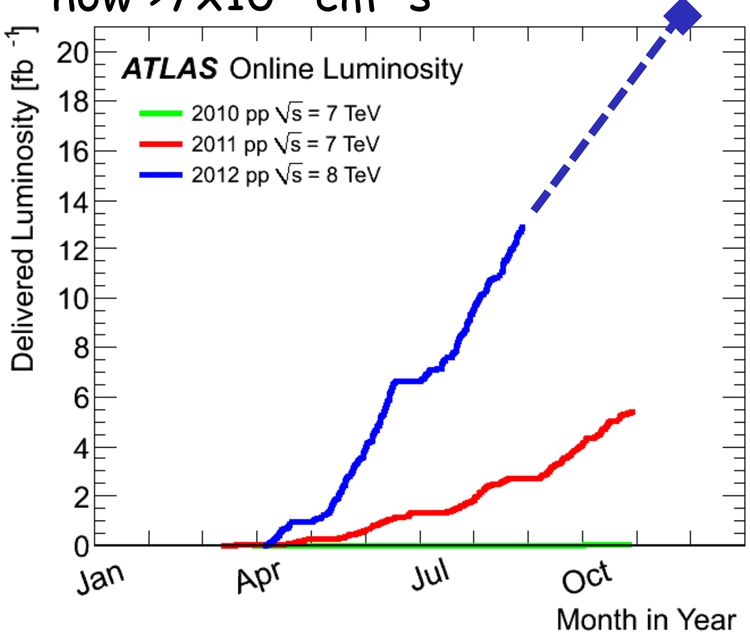
The ATLAS DBM Concept
DBM Design
DBM Status
Summary

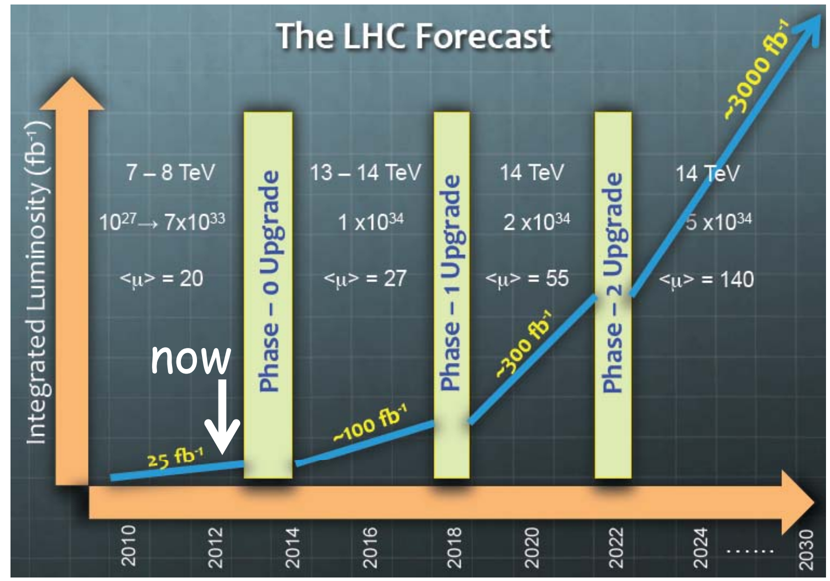
Diamond Beam Monitor Motivation

Many precision measurements limited by luminosity determination
(e. g. absolute cross section measurements, pp→HiggsX, WZX,…)

Rapid increase in LHC Luminosity
– now >$7 \times 10^{33} cm^{-2} s^{-1}$

....And L will continue to grow!





$$L = \mu(n_b f_r)/\sigma_{inel}$$

μ=average # of inelastic interactions per bunch crossing

n_b= # of colliding bunch pairs
f_r= machine revolution frequency
} LHC parameters

σ_{inel}= inelastic cross section

Luminosity is a counting issue: requires good segmentation in space or time

Problems occur when μ can not be reliably measured

Diamond Beam Monitor Motivation

In order to make a precise determination of the luminosity at the highest instantaneous luminosity & energy we need a detector that is:

- radiation hard: accumulate $2\times10^{15}\ n_{eq}/cm^2$
- fast: ~nsec resolution, resolve beam bunches
- stable/reliable: last for ~ "10 years"
- sensitive to charged particles: prefer min. ionizing

Diamond is a good sensor candidate...

- ☺radiation hard
- ☺short collection time
- ☺low leakage current
- ☺excellent thermal conductor
- ☹signal size ~2.5 less than silicon for same thickness

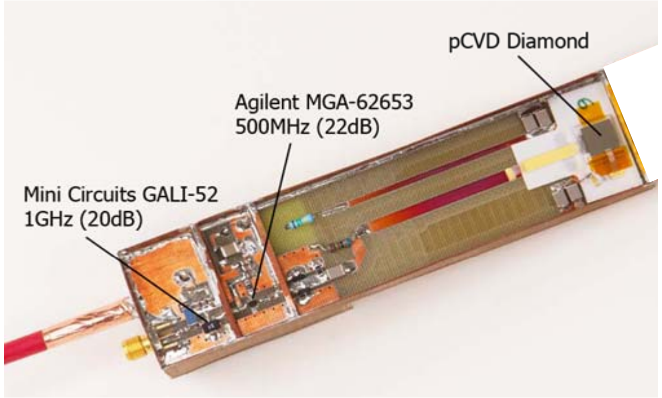
ATLAS already has 2 diamond based systems

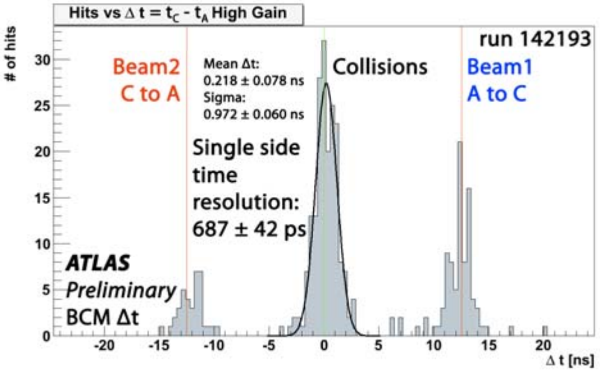
Beam Conditions Monitor (BCM)

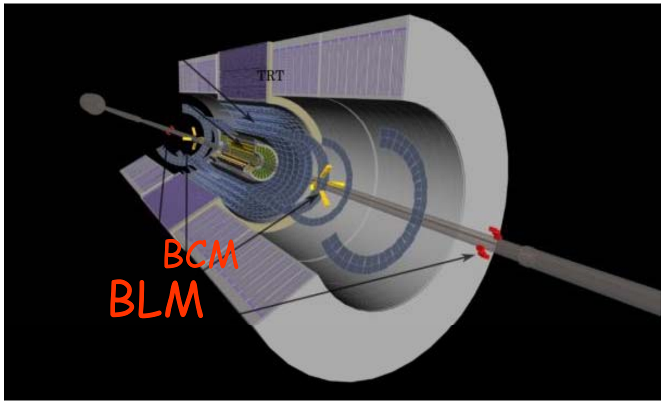
16 pCVD diamonds (1 x 1 cm^2)
z=±184 cm, r=5.5 cm , |η|=4.2

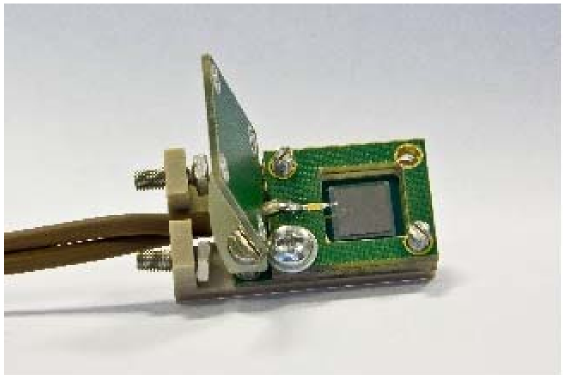
Beam Loss Monitor (BLM)

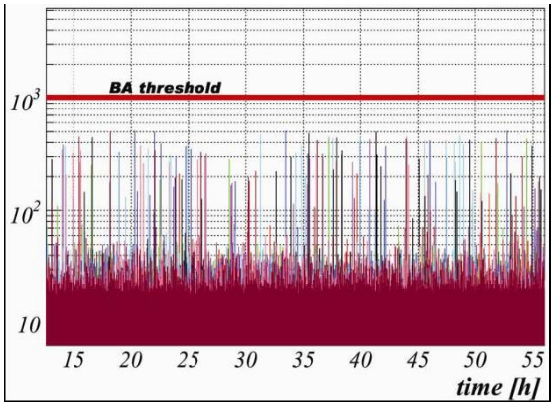
12 pCVD diamonds, 6 per side
z=±345cm, r=6.5 cm











Both of these systems monitor the LHC beams:

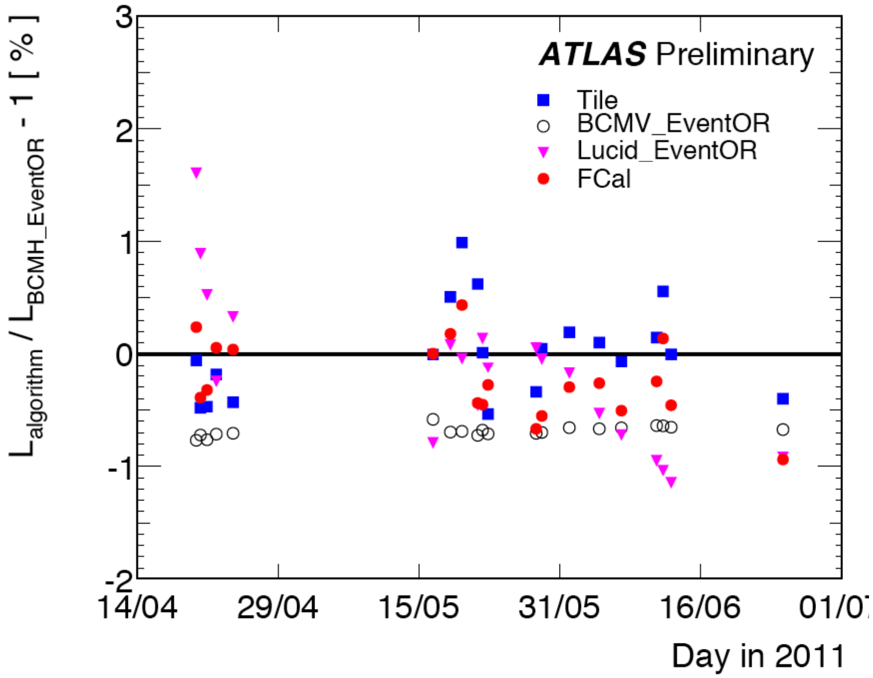
- **can abort the LHC beams**
- **essential for determining luminosity**

DBM Motivation: lessons learned

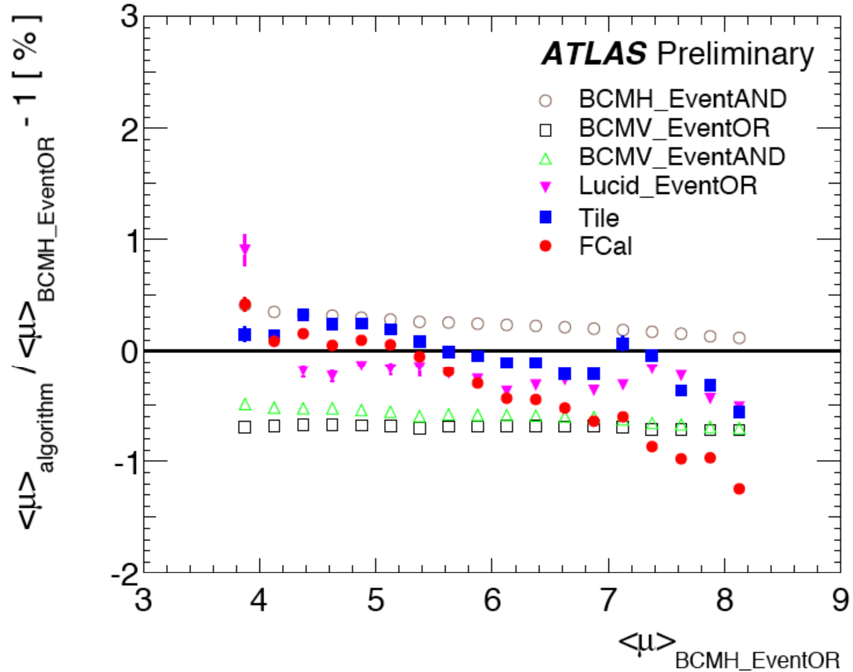
Two independent luminosity measurements BCMH & BCMV:

(H=horizontal, V=vertical)

Stable over months



Stable against pile-up

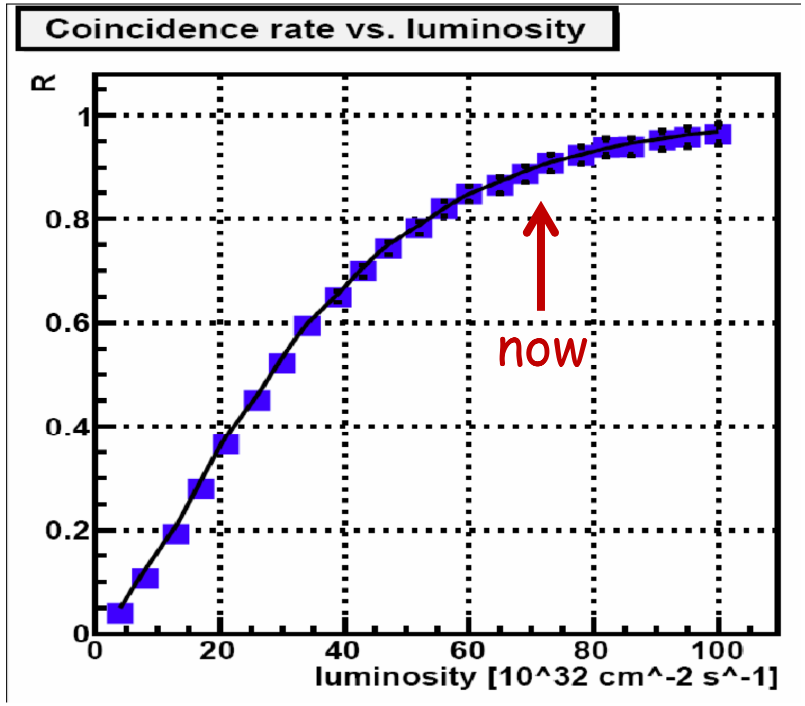


In 2012 BCM achieved a 1.9% luminosity measurement!

(BUT issues with vDM scans increased systematic error to ~3.5%)

DBM Motivation

The BCM will begin to saturate at ~10^{34} $cm^{-2}s^{-1}$:



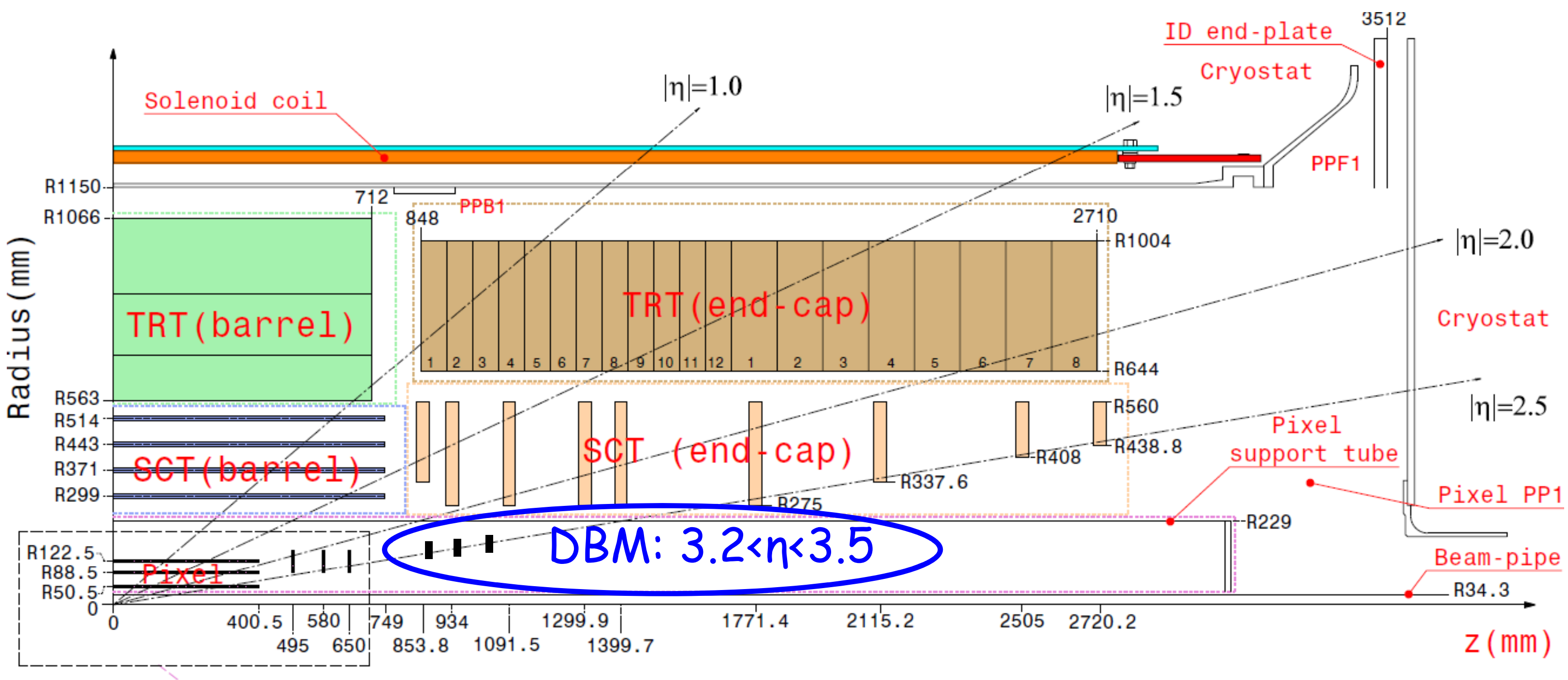
More segmentation → Diamond Beam Monitor (DBM)

Increase number of channels by ~ 10^5

The ATLAS DBM Concept

Build on success of BCM – pixelate the sensors

- Use IBL diamond pixel demonstrator module
  - use many of the same pieces (FEI4, etc) as IBL to save time/money
  - same segmentation as IBL sensors, 50 x 250 μm^2
- Install during new Service Quarter Panel (nSQP) replacement
- Four 3-plane stations on each side of the IR

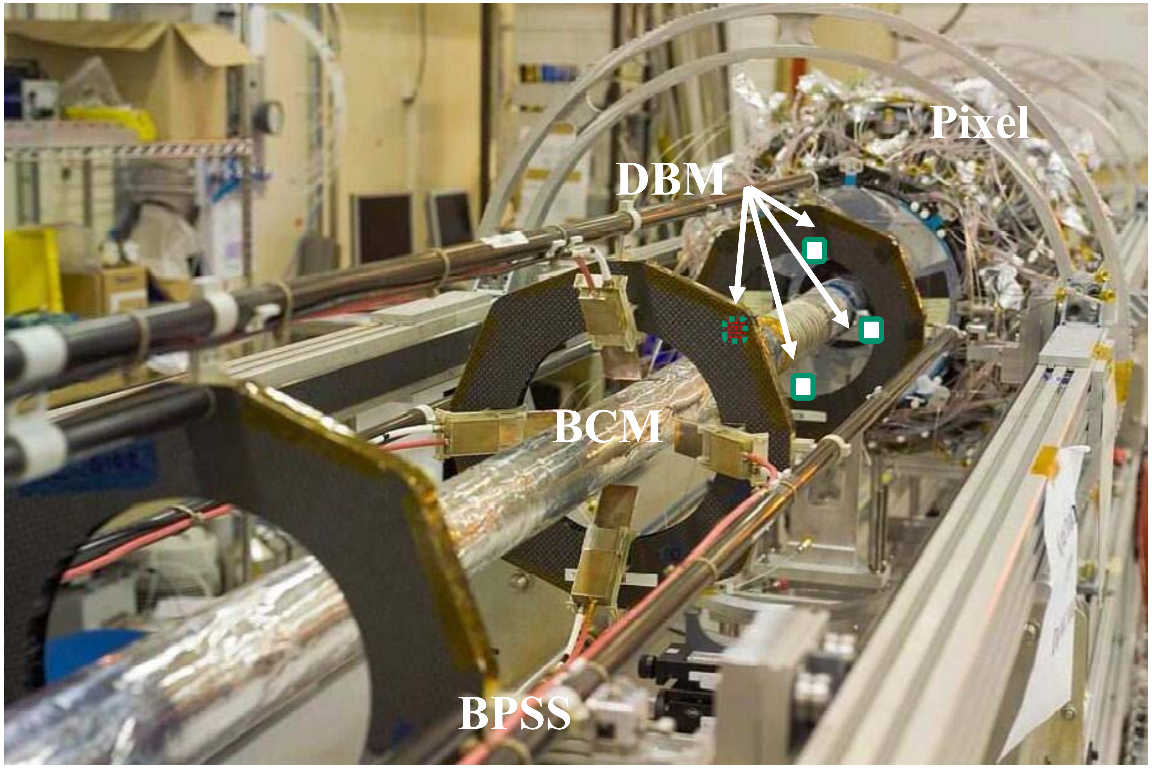


The ATLAS DBM Concept

24 diamond pixel modules arranged in 8 telescopes provide

- Bunch by bunch luminosity monitoring
- Bunch by bunch beam spot monitoring

Installation happening now!



The ATLAS DBM Specs and Collaboration

Specs:

- Bunch by bunch luminosity monitoring (<1% stats/sec)
- Bunch by bunch beam spot monitoring (unbiased sample, ~ 1cm)

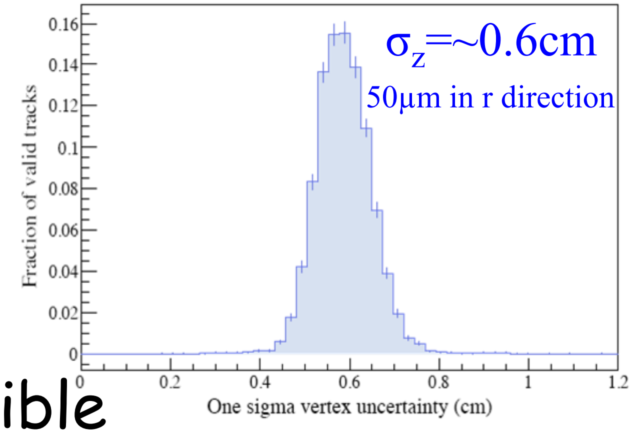
Bonn CERN Göttingen Ljubljana N.Mexico OhioSt Toronto

The ATLAS DBM Concept

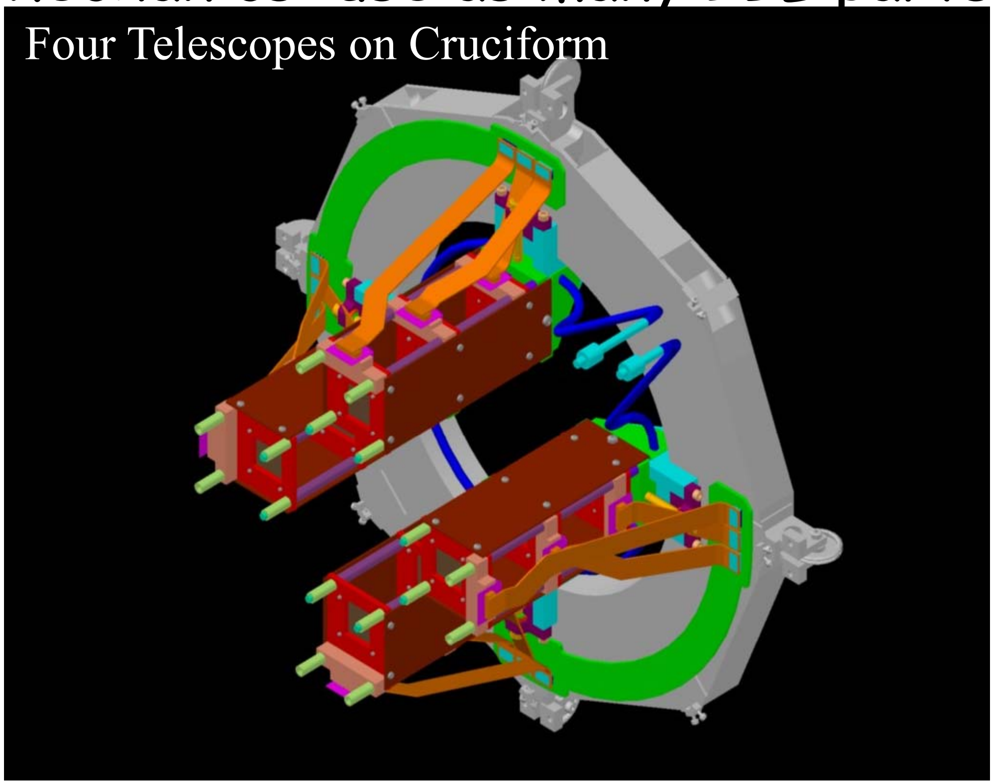
Simulate DBM to find best orientation and resolution

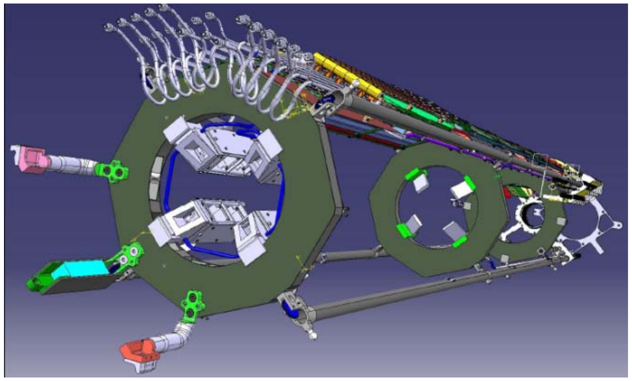
Focus on z vertex resolution

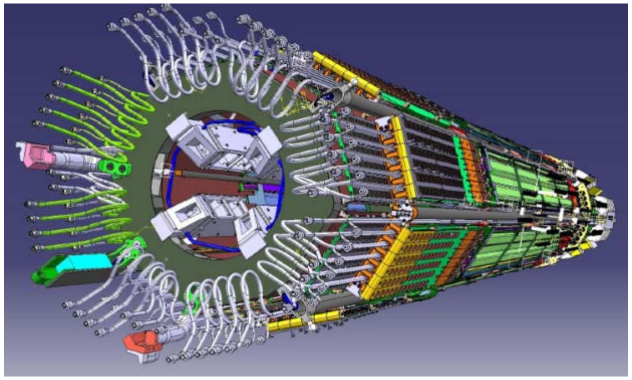
3 layers of tracking with 50 x 250 μm^2 pixel cell



Mechanics: use as many IBL parts as possible







DBM Diamond Sensor Plan

Diamond Sensors for DBM:

Type: polycrystalline CVD diamond
Charge collection distance > 250 μm
(as measured with Sr90 source)
Size: 21 x 18 mm^2, 525 ± 25 μm thickness
Number: 24 for DBM modules + spares
5 for Irradiation studies

21 x 18 mm^2 pCVD diamond

Two diamond suppliers involved:

II-VI (US based)

Diamond Detectors Limited (DDL)/E6 (UK based)

☹ DDL ceases operations while filling our order....

How much Diamond is in the DBM?

About as much as in the diamond Richard Burton bought for Liz Taylor in 1969

~ 70 carats

Auctioned in 1978 for $5M

http://en.wikipedia.org/wiki/Taylor-Burton_Diamond

Each DBM sensor is ~ 3.2 carats

(1 carat= 200 mg)

Entire DBM: 24 sensors

~ 76 carats!

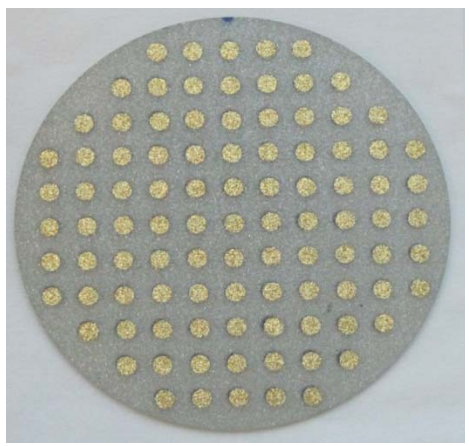
Price of all DBM diamond < $150k

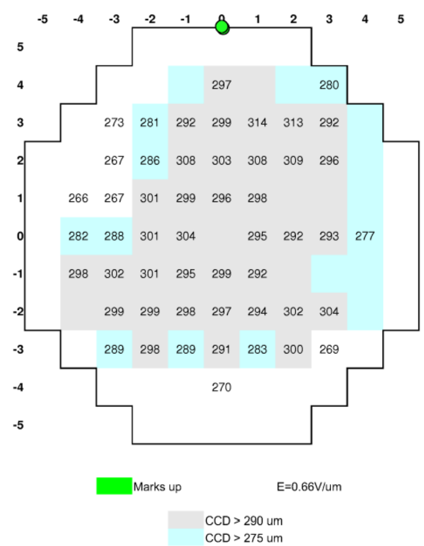
DBM Diamond Sensor Qualification

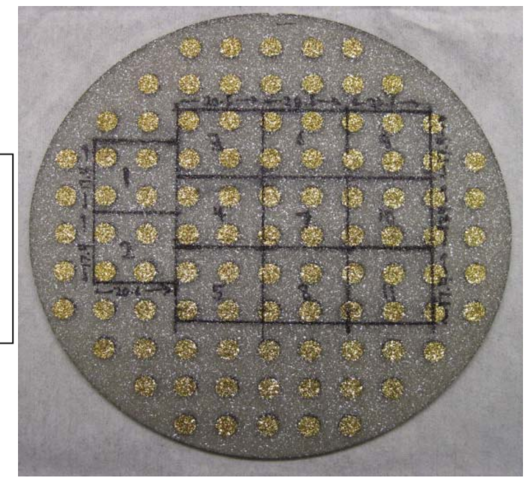
At OSU we put conducting contacts ("gold dots") on the diamond & measure the charge collection properties in the region of each dot.

Use Sr90 as a source of particles for charge collection measurements

5 inches







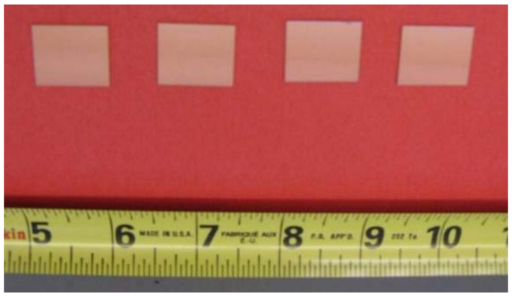
We also make a map of the current draw as we measure CCD

Good regions have I < 5 nA at 1000V in air

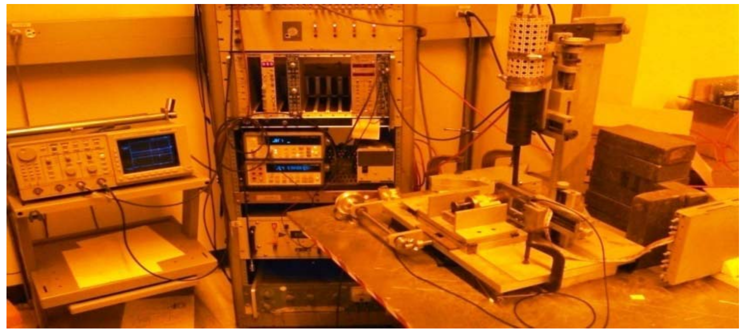
DBM Module Production

Wafer is cut into pieces and shipped back to OSU

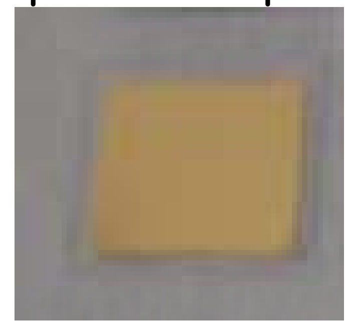
sensors



collection distance re-measured

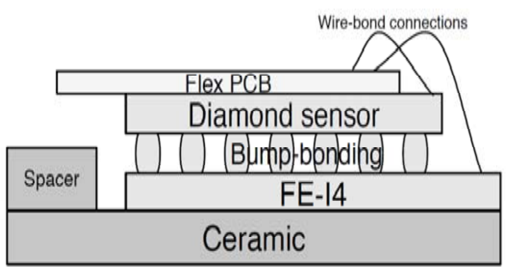


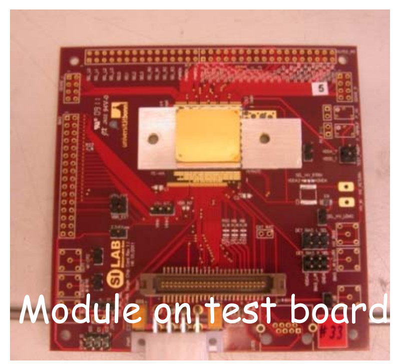
backplane is deposited

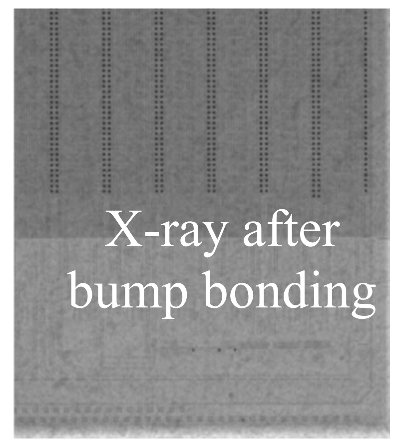


Sensors are sent to IZM to be made into modules

put pixel pattern on diamond
bump bond diamond to FEI4





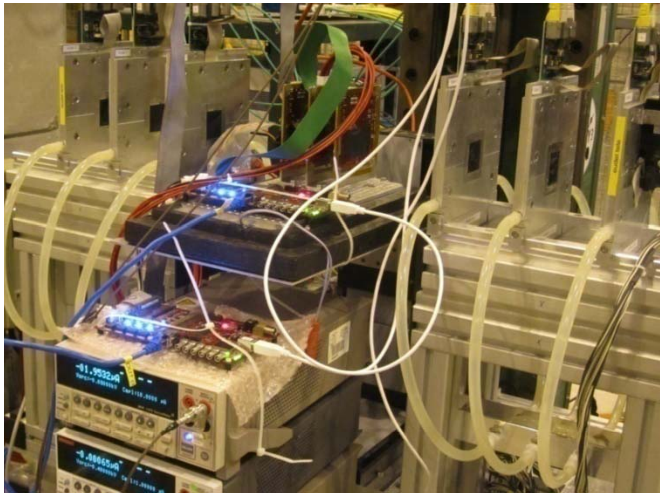


DBM Module Testbeam Studies

Three Testbeam campaigns

Learning about FE-I4 performance

Calibration/tunings for low threshold performance



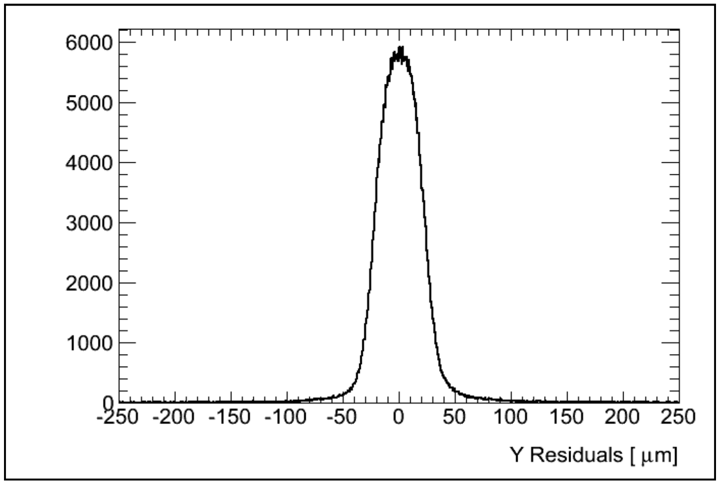
Prototype Modules Tested:

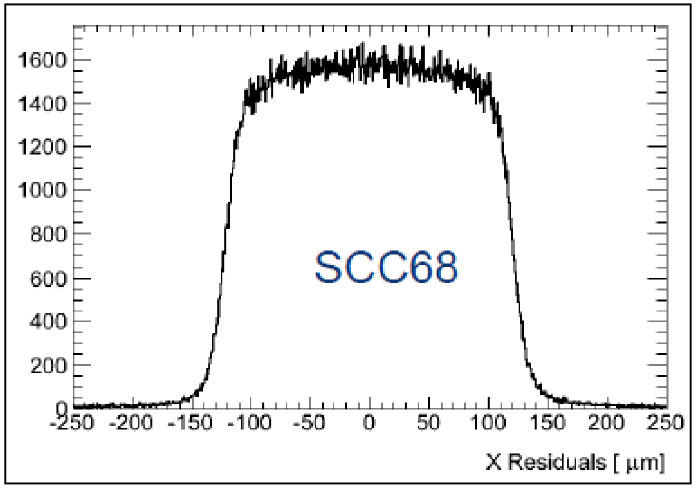
21mmx 18mm pCVD diamond w/FE-I4A

336 x 80 = 26880 channels

50 x 250 μm^2 pixel cell

Results: Noise map uniform, Efficiency >95%, spatial resolution digital





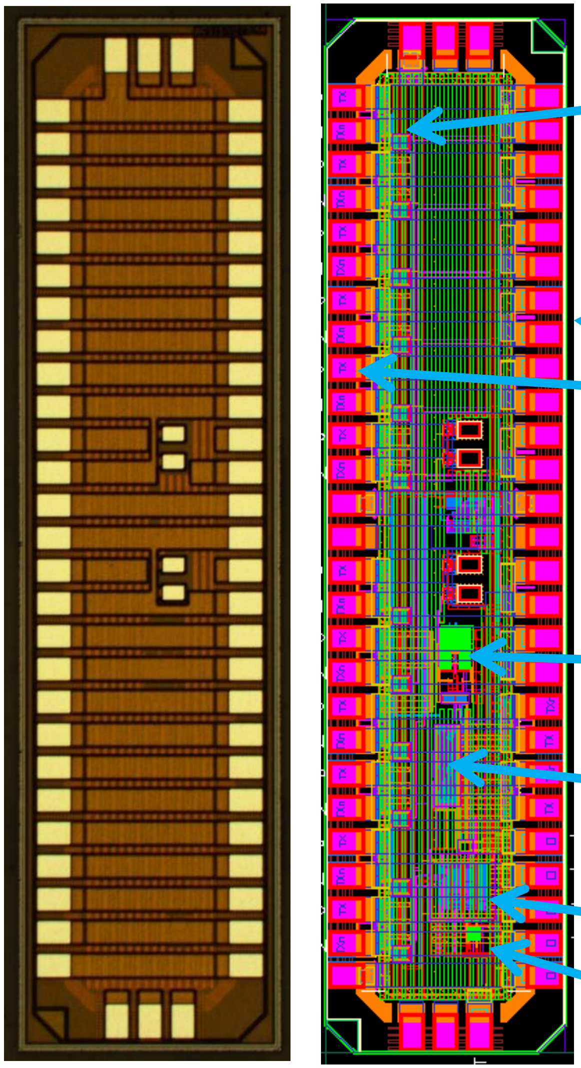
OSU's DBM Hitbus Chip Overview

ASIC developed to provide L1A trigger for the DBM by using the FEI4 Hitbus outputs

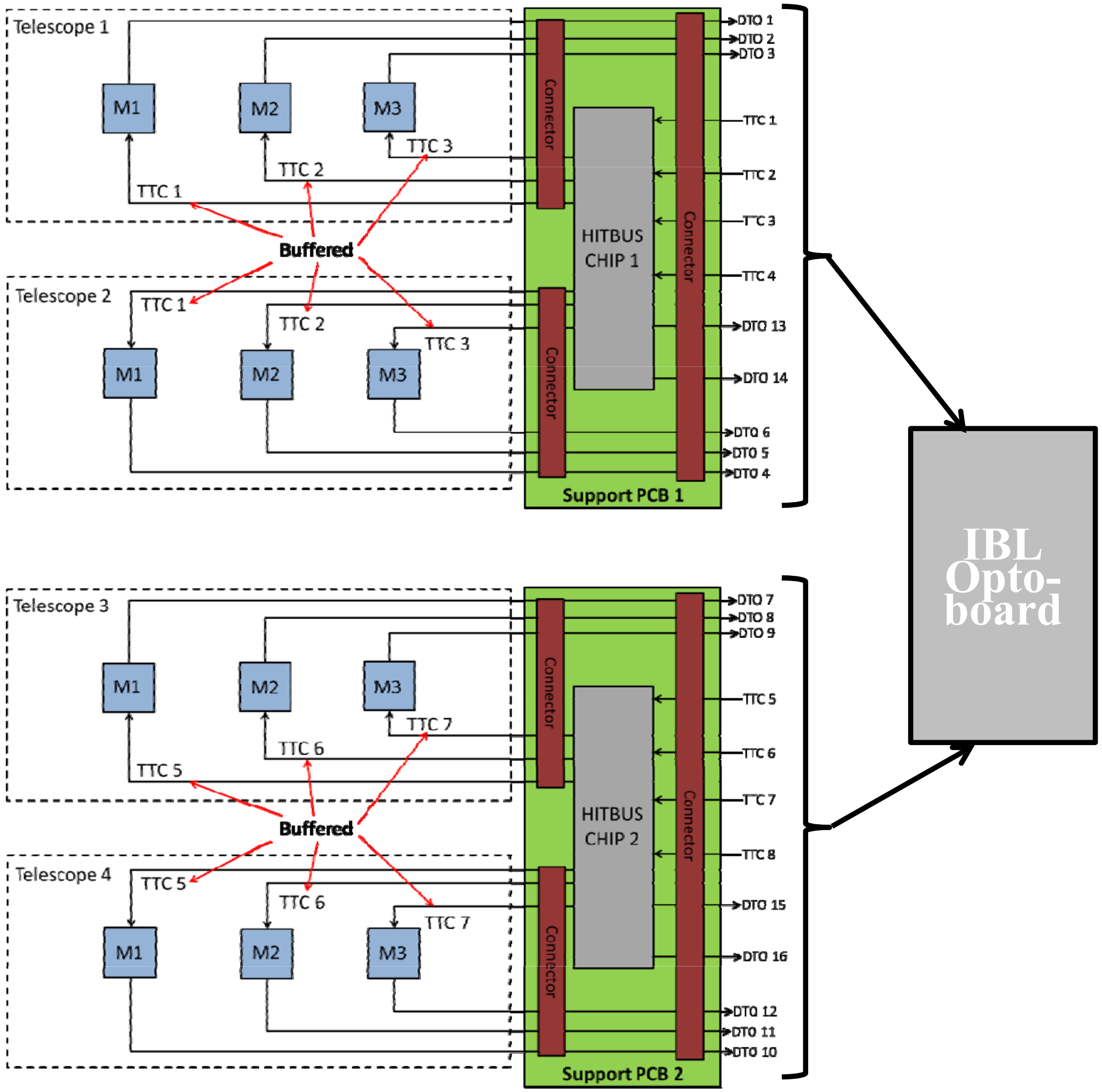
Each DBM hitbus chip services 2 telescopes so 4 chips needed for entire DBM

Use IBM 130nm 8RF CMOS
Size: 4.59 mm x 1.06mm

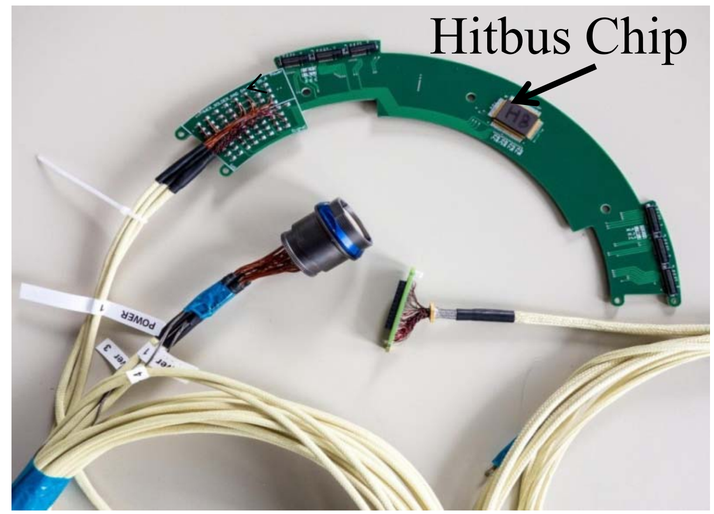
Incorporates shared circuit blocks from FEI4 collaboration & custom blocks designed at OSU



Half DBM System Block Diagram



2 Support PCBs/side

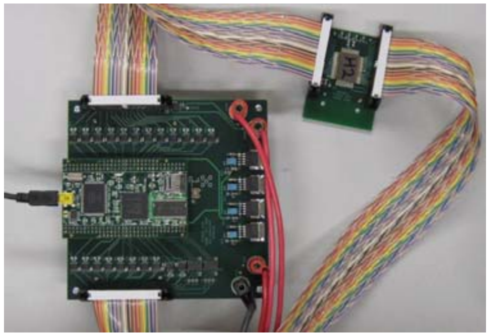


Hitbus Chip Irradiation

Needed to certify that Hitbus Chip is rad hard

Irradiated 2 Hitbus chips to 4.3 x 10^{15} p/cm^2 (115 Mrad)

Used 24 GeV proton beam at CERN



Both chips survived

Slight increase in supply current consumption

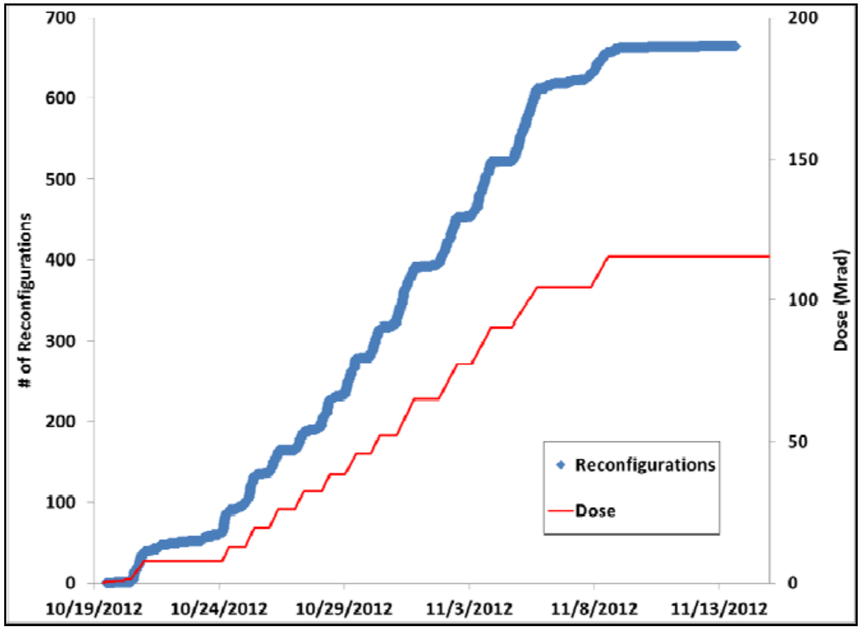
All functionality active during irradiation

Test system checked for SEU in the received data

Looked for flipped bits in SEU latches change of Hitbus desired function

Reconfigured the chip if error detected

Only 664 reconfiguration events needed (for both chips)



Current Status of DBM

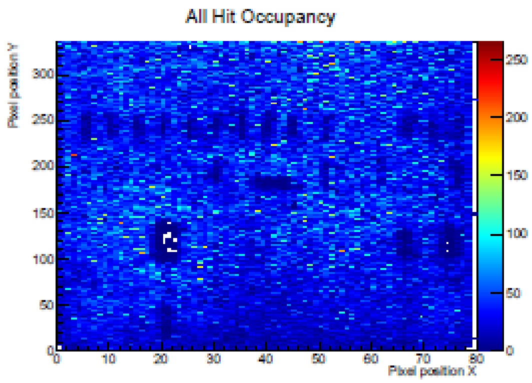
DBM currently being assembled at CERN

Potentially ~30 modules constructed

- Modules still being processed at IZM

In the process of picking the best 24 modules to be installed

- Measure I vs V to find range of operation
- Sr90 source scan on each module
  - find disconnected pixels (bad bump bonds)
  - find noisy pixels
  - measure relative efficiency vs V and threshold
  - measure clusters vs threshold



Modules will be assembled into telescopes in ~ week

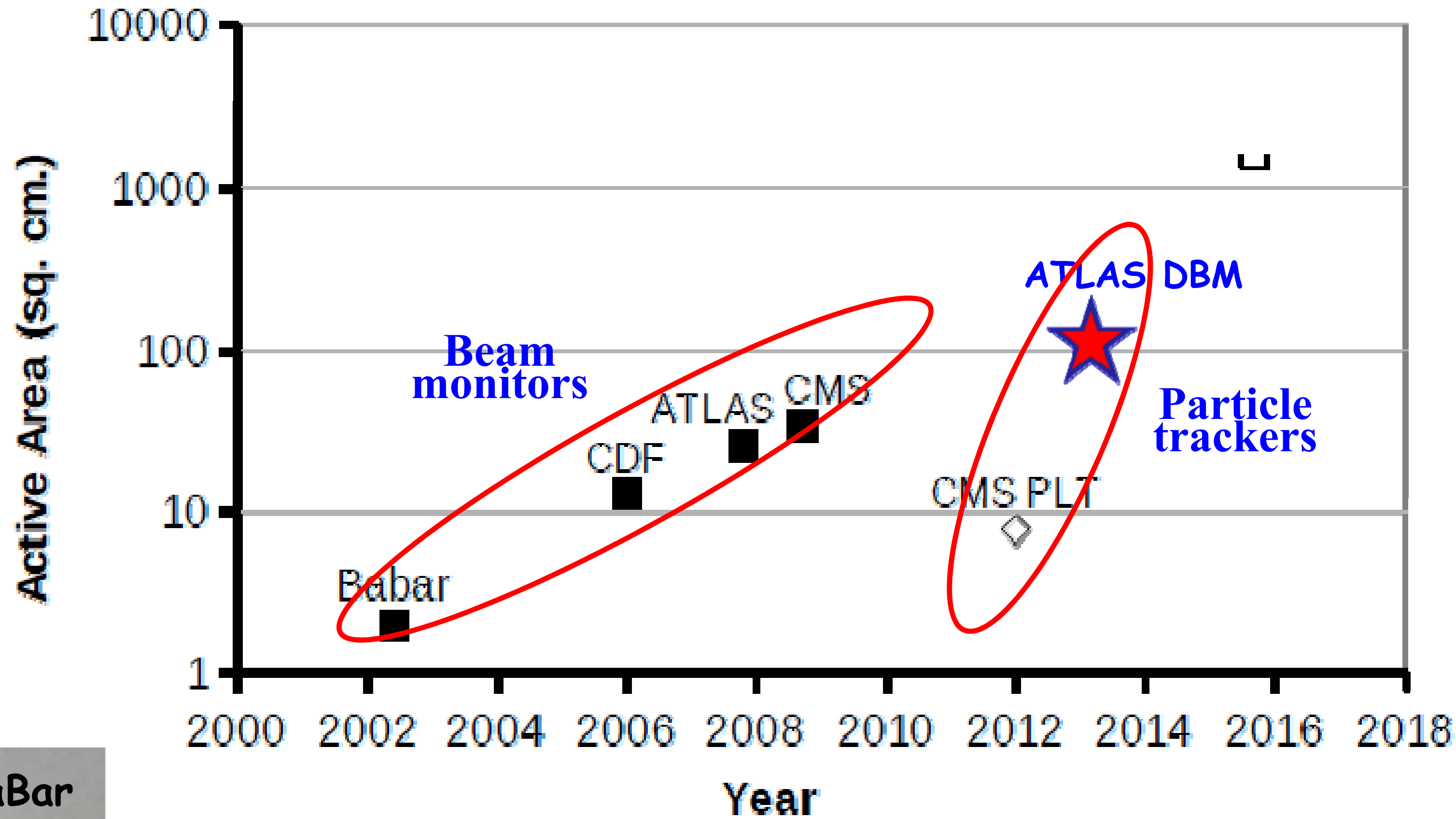
- telescope = group of three modules, total of 8 telescopes in DBM

Telescopes installed in September

DBM and Other Diamond Projects

DBM has ~ 6.25×10^5 channels

(LEP's DELPHI pixel detector ~ 12×10^5 channels)



BaBar beam monitor:
two pCVD diamonds
1 cm x 1 cm x 500 µm

Summary

- Construction of the largest diamond pixel tracker underway
- Satisfies constraints for precision luminosity measurement
  - Bunch by bunch measurement
  - Background separation uses z resolution
- Should be robust against
  - Pile-up
  - Radiation damage

ATLAS Diamond Beam Monitor TDR: ATU-DBM-001

Backup Slides

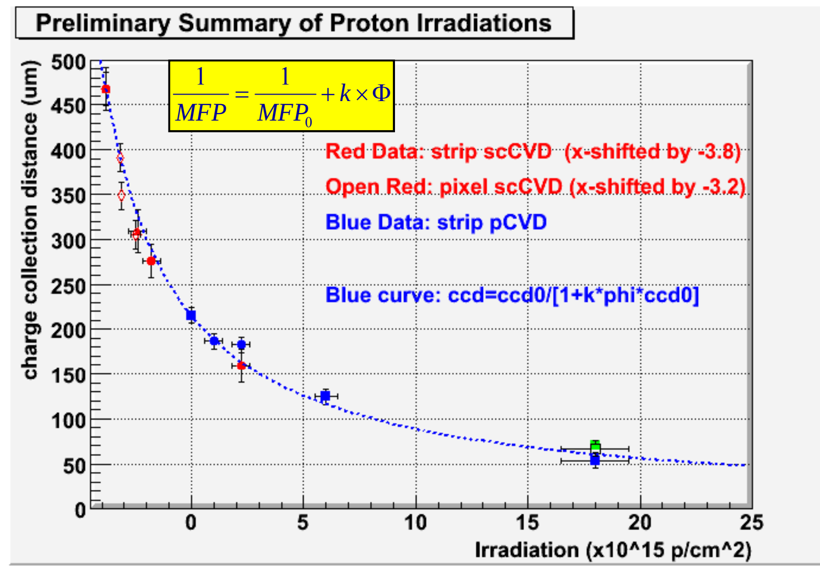
Chemical Vapor Deposition Diamond

The properties of diamond make it interesting/useful for particle detectors:
radiation hard, short collection time, low leakage current, high thermal conductivity

Diamond as sensor material

Property	Diamond	Silicon
Band gap [eV] Low leakage	5.5	1.12
Breakdown field [V/cm]	10^7	3×10^5
Intrinsic resistivity @ R.T. [Ω cm]	> 10^{11}	2.3×10^5
Intrinsic carrier density [cm^{-3}]	< 10^3	1.5×10^{10}
Electron mobility [cm^2/Vs]	1900	1350
Hole mobility [cm^2/Vs]	2300	480
Saturation velocity [cm/s]	0.9(e)-1.4(h)x 10^7	0.82x 10^7
Density [g/cm^3]	3.52	2.33
Atomic number - Z	6	14
Dielectric constant – ε Low cap	5.7	11.9
Displacement energy [eV/atom] Rad hard	43	13-20
Thermal conductivity [W/m.K] Heat spreader	~2000	150
Energy to create e-h pair [eV]	13	3.61
Radiation length [cm]	12.2	9.36
Interaction length [cm]	24.5	45.5
Spec. Ionization Loss [MeV/cm]	6.07	3.21
Aver. Signal Created / 100 μm [e_0] Low Noise, Low signal	3602	8892
Aver. Signal Created / 0.1 X_0 [e_0]	4401	8323

Radiation Studies



Single-crystal CVD & poly CVD fall along the same damage curve

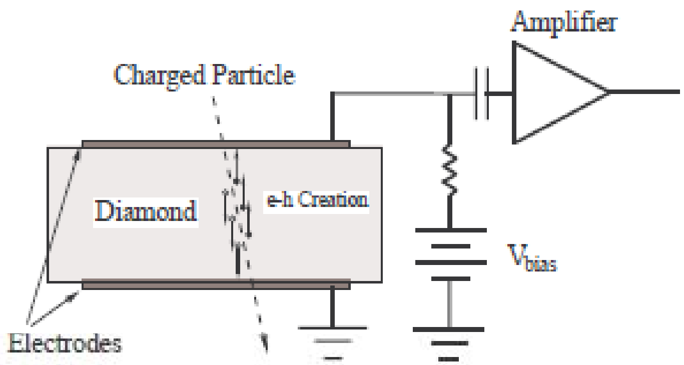
Proton damage well understood

At all energies diamond is >3x more radiation tolerant than silicon

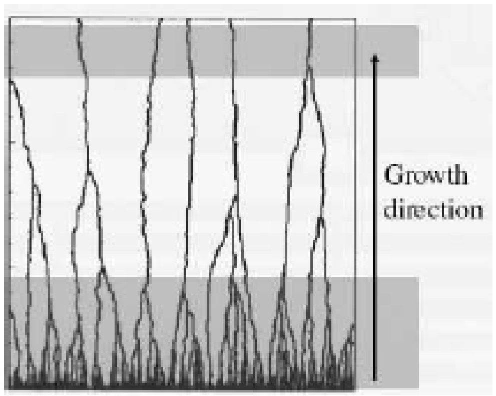
Charge Collection in CVD Diamond

Detectors Constructed with Diamond:

Signal formation



pCVD Schematic Side View



- d=$(\mu_e\tau_e + \mu_h\tau_h)$E where d = collection distance = ave. dist. e-h pair move apart
- d=μEτ = vτ

  with $\mu = \mu_e + \mu_h \rightarrow$ v = μ E

  and $\tau = \frac{\mu_e\tau_e + \mu_h\tau_h}{\mu_e + \mu_h}$
- Q=$\frac{d}{t}Q_0$ $\rightarrow$ for large charge need good collection distance - must maximize μ and τ
- I=$Q_0\frac{v}{d}$

Diamond Specs

Property	Specifications
Sensor size	21mm x 18mm (active area 20mm x 16.8mm)
Sensor Thickness	400-500 microns
Minimum charge collection distance	200 microns
Minimum average charge	7200 electrons
Minimum collection distance/ charge after $2x10^{15}$ cm^{-2}	100 microns/3600 electrons
Minimum signal/threshold after $2x10^{15}$ cm^{-2}	3
Maximum operating voltage	1000 V
Maximum total leakage current (@1000 V)	100 nA

Radiation Damage - Basics

Radiation induced effect	Diamond	Operational consequence	Silicon	Operational consequence
Leakage current	small & decreases	none	I/V = $\alpha\Phi$ $\alpha \sim 4\text{x}10^{-17}$ A/cm	Heating Thermal runaway
Space charge	~ none	none	$\Delta N_{eff} \approx -\beta\Phi$ $\beta \sim 0.015$ cm^{-1}	Increase of full depletion voltage
Charge trapping	Yes	Charge loss Polarization	$1/\tau_{eff} = \beta\Phi$ $\beta \sim 5\text{-}7\text{x}10^{-16}$ cm^2/ns	Charge loss Polarization

Charge trapping the only relevant radiation damage effect

NIEL scaling questionable *a priori*

E_{gap} in diamond 5 times larger than in Si

Many processes freeze out

Typical emission times order of months

Like Si at 300/5 = 60 K – Boltzmann factor

A rich source of effects and (experimental) surprises !

$$\frac{1}{\tau_{eff}} = \sum_t N_t (1 - P_t) \sigma_t v_{th}$$

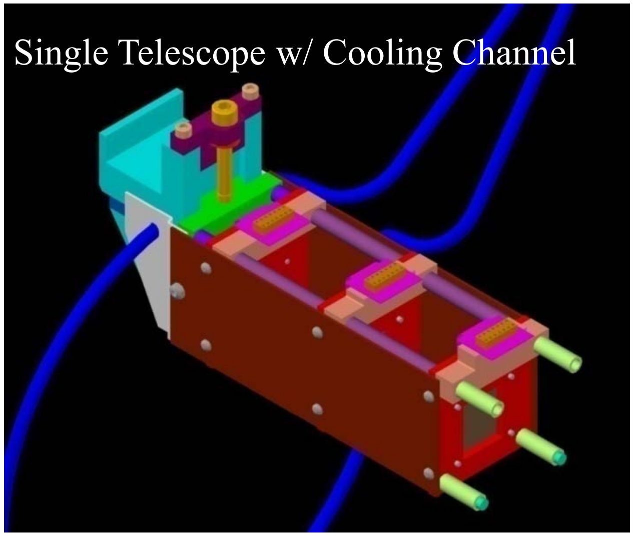
Summary of RD42 Test Beam Results for CVD Diamond

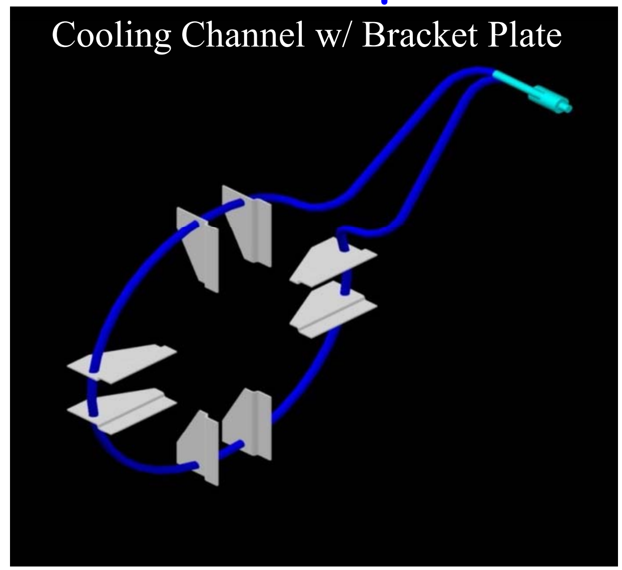
Particle	Energy	Relative k
p	24GeV	1.0
	800MeV	1.6-1.8
	70MeV	2.5-2.8
	25MeV	4.0-5.0
π	200MeV	2.5-3.0

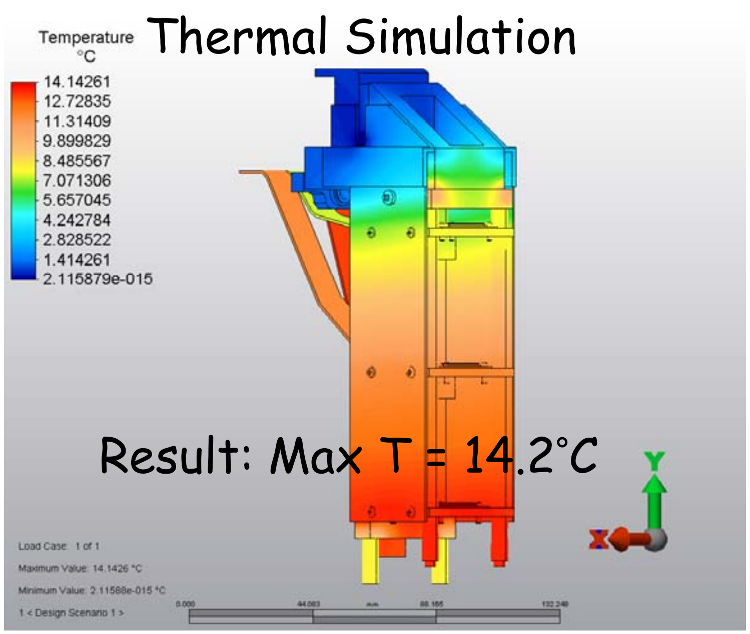
k is relative damage constant

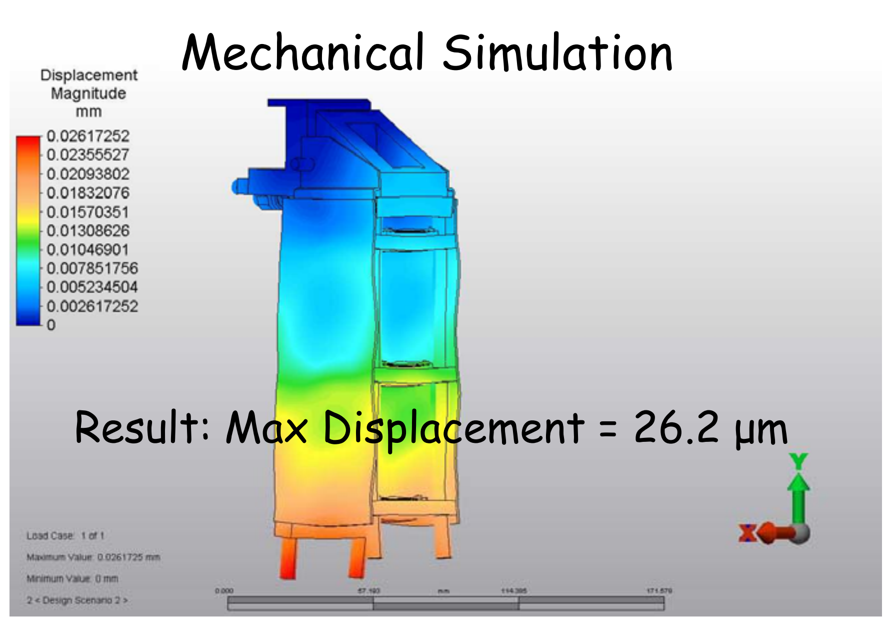
The ATLAS DBM Concept

Thermal & mechanical simulations complete

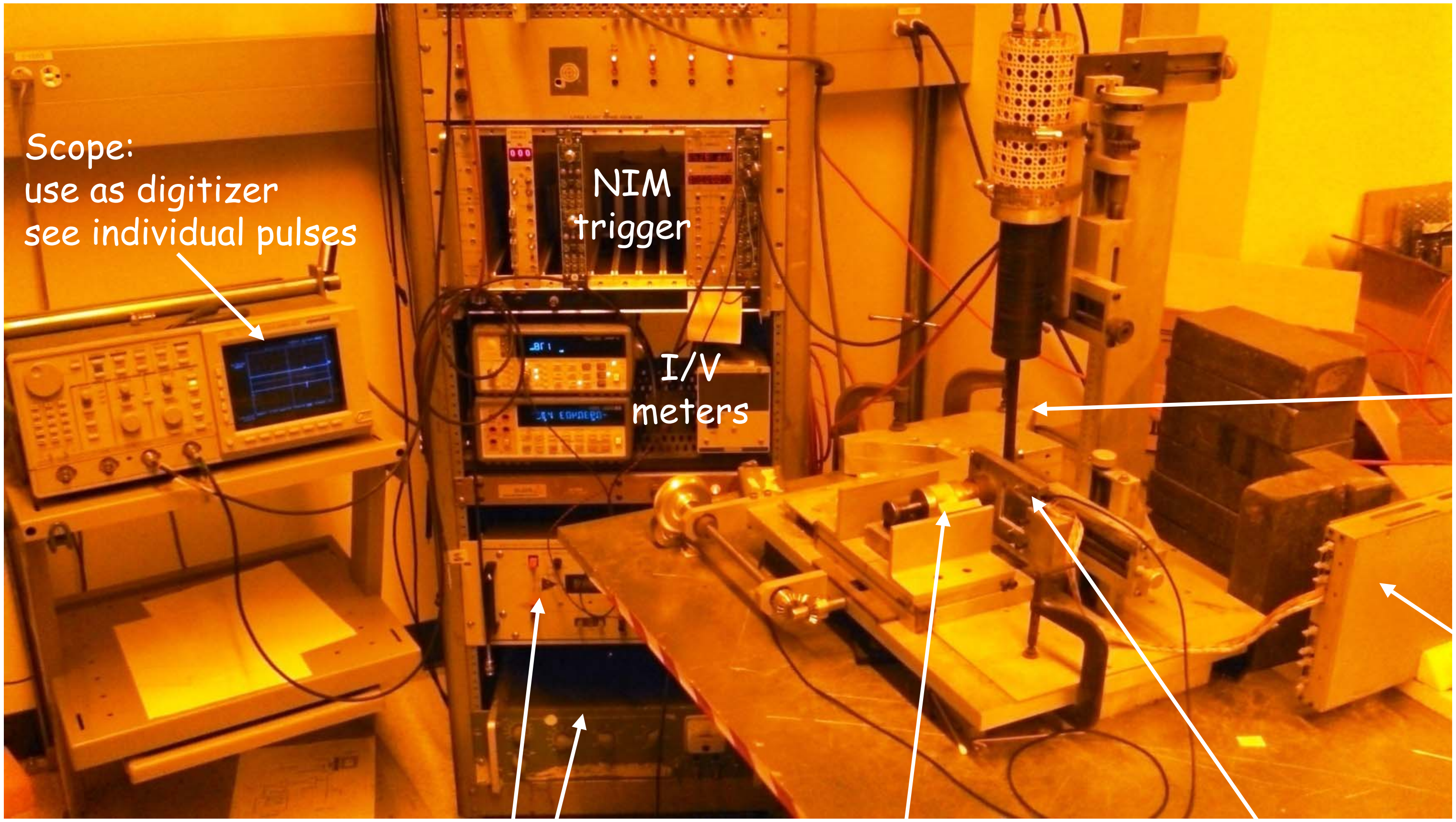


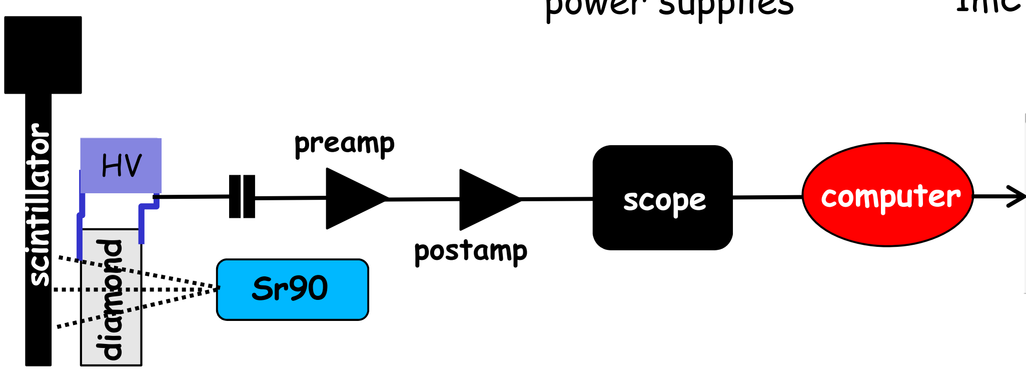


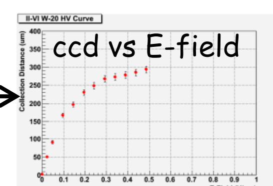


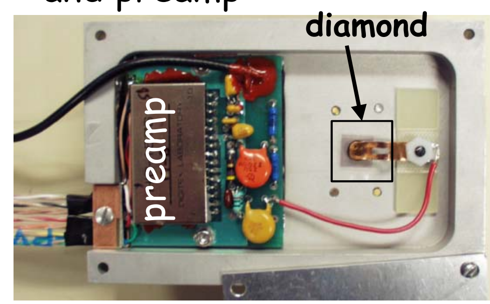


CCD measurement with Sr90 @ OSU

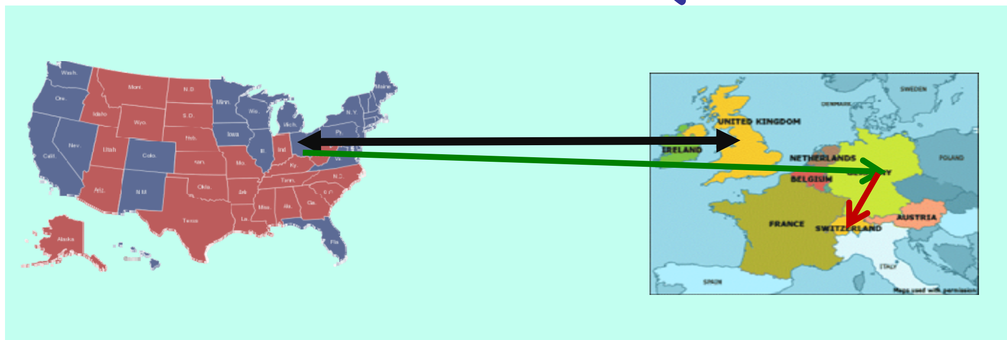


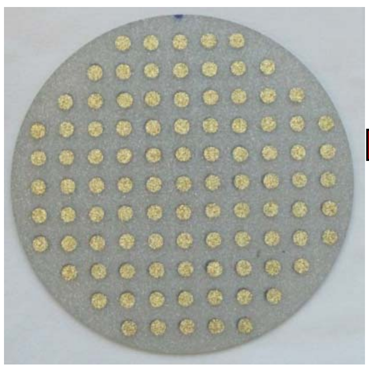






DBM Diamond Sensor Qualification





Map of charge collection distances

	-5	-4	-3	-2	-1	0	1	2	3	4	5
5											
4						297			280		
3			273	281	292	299	314	313	292		
2			267	286	308	303	308	309	296		
1		266	267	301	299	296	298				
0		282	288	301	304		295	292	293	277	
-1		298	302	301	295	299	292				
-2			299	299	298	297	294	302	304		
-3			289	298	289	291	283	300	269		
-4						270					
-5											

Marks up E=0.66V/um

CCD > 290 um
CCD > 275 um

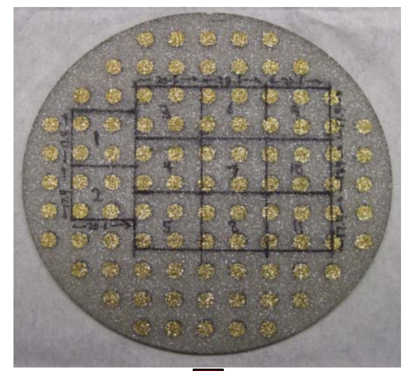
Map of current draw

	-5	-4	-3	-2	-1	0	1	2	3	4	5
5											
4						2.2			2.7		
3			2.2	2.4	2.4	2.1	2.4	2.4	2.3		
2			2.4	2.3	2.3	2.1	2.4	2.2	2.2		
1		2.4	2.4	2.4	2.2	2.4	2.2				
0		2.3	2.1	2.2	2.3		2.3	2.2	2.2	2.3	
-1		2.5	2.4	2.3	2.1	2.3	2.2				
-2			2.4	2.2	2.3	2.2	2.3	2.2	2.4		
-3			2.3	2.4	2.3	2.3	2.3	2.4	2.2		
-4						2.2					
-5											

Marks up V=1000V

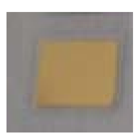
CCD > 290 um
CCD > 275 um

"Cut" map
This wafer will be cut into 11 sensors



Back to manufacturer for dicing & thinning

Back to OSU re-test with Sr90, metalize backplane

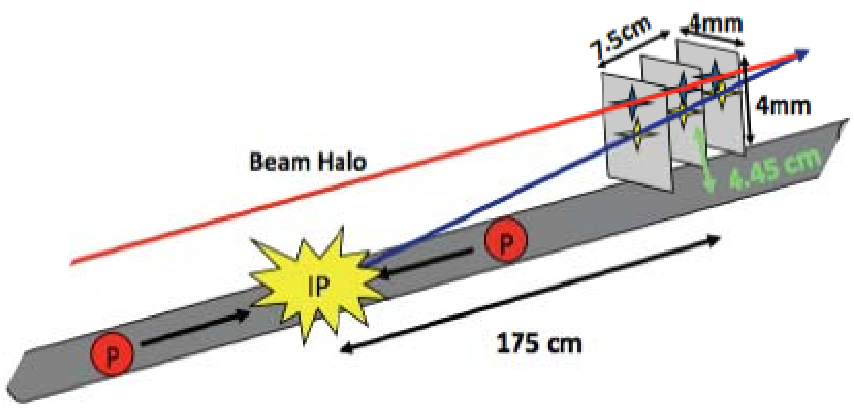


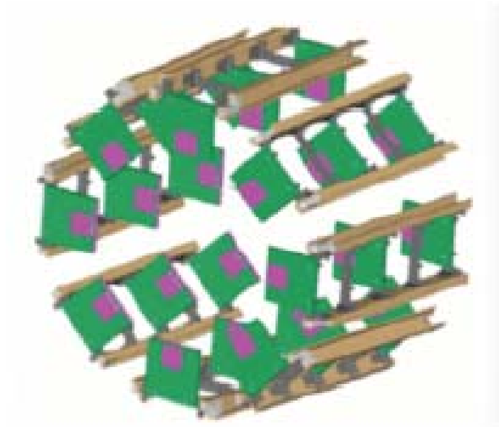
To IZM for bump bonding, etc

CMS Pixel Luminosity Telescope

Dedicated stand-alone luminosity monitor for CMS

- High precision bunch-by-bunch luminosity
- Array of 3-plane telescopes each end of CMS
- Single-crystal diamond pixel sensors
- Measure bunch-by-bunch 3-fold coincidence rate
- Pixel readout for tracking and diagnostics





Install in CMS in 2013-2014 shutdown